

Investigation of the Effects of Cathode Flow Fraction and Position on the Performance and Operation of the High Voltage Hall Accelerator

Hani Kamhawi*, Wensheng Huang†, and Thomas Haag‡,
NASA Glenn Research Center, Cleveland, Ohio, 44135

The National Aeronautics and Space Administration (NASA) Science Mission Directorate In-Space Propulsion Technology office is sponsoring NASA Glenn Research Center (GRC) to develop a 4 kW-class Hall thruster propulsion system for implementation in NASA science missions. Tests were performed within NASA GRC Vacuum Facility 5 at background pressure levels that were six times lower than what has previously been attained in other vacuum facilities. A study was conducted to assess the impact of varying the cathode-to-anode flow fraction and cathode position on the performance and operational characteristics of the High Voltage Hall Accelerator (HiVHAc) thruster. In addition, the impact of injecting additional xenon propellant in the vicinity of the cathode was also assessed. Cathode-to-anode flow fraction sensitivity tests were performed for power levels between 1.0 and 3.9 kW. It was found that varying the cathode flow fraction from 5 to approximately 10% of the anode flow resulted in the cathode-to-ground voltage becoming more positive. For an operating condition of 3.8 kW and 500 V, varying the cathode position from a distance of closest approach to 600 mm away did not result in any substantial variation in thrust but resulted in the cathode-to-ground changing from -17 to -4 V. The change in the cathode-to-ground voltage along with visual observations indicated a change in how the cathode plume was coupling to the thruster discharge. Finally, the injection of secondary xenon flow in the vicinity of the cathode had an impact similar to increasing the cathode-to-anode flow fraction, where the cathode-to-ground voltage became more positive and discharge current and thrust increased slightly. Future tests of the HiVHAc thruster are planned with a centrally mounted cathode in order to further assess the impact of cathode position on thruster performance.

I. Introduction

NASA Science Mission Directorate (SMD) In-Space Propulsion Technology (ISPT) Project funds new electric propulsion (EP) system development for future NASA science missions.¹ The two primary EP elements of this project are the development of NASA's Evolutionary Xenon Thruster (NEXT) ion thruster propulsion system² for NASA Discovery, New Frontiers and Flagship-class missions and the development of a long-life High Voltage Hall Accelerator (HiVHAc) as a lower cost EP option for NASA Discovery-class science missions.

In addition to the mission performance benefits that can be realized with EP systems,³ significant cost savings can be achieved by using a Hall thruster system when compared to gridded ion and chemical propulsion systems.⁴ The Hall thruster system option will not only enable a wide range of Discovery-class missions but will enable science return far greater than the chemical alternatives.⁵

As part of the HiVHAc thruster development, a study was performed to assess how the HiVHAc thruster operational characteristics and performance change at background pressure levels that are six to ten times lower than what has been reported in the past.^{5,6} HiVHAc thruster tests in VF5 included tests to assess how the thruster performance changes as a function of the facility background pressure. A companion paper by Kamhawi et al. is reporting on the results of that test campaign.⁷ Tests of the HiVHAc thruster at NASA Glenn Research Center (GRC) Vacuum Facility 5 (VF5) found that the HiVHAc thruster performance in VF5 was lower than what was measured in Vacuum Facility 12 (VF12). In addition, HiVHAc thruster tests in VF5 included a parametric study to

* Senior Research Engineer, In-Space Propulsion Branch, hani.kamhawi-1@nasa.gov.

† Research Engineer, In-Space Propulsion Branch, wensheng.huang@nasa.gov.

‡ Senior Propulsion Engineer, In-Space Propulsion Branch, thomas.w.haag@nasa.gov.

evaluate how the HiVHAc thruster operation and performance change as a function of the cathode-to-anode flow fraction (hereafter referred to as cathode flow fraction), injection of auxiliary propellant in the vicinity of the cathode, and cathode position. The objective of this study is to determine the HiVHAc thruster cathode flow fraction that will provide stable thruster operation and optimum performance at low background pressure conditions. In addition, the team wanted to investigate whether injection of additional propellant flow in the plume region of the cathode would enhance the operational stability and performance of the thruster. Finally, a cathode position study was performed to investigate whether there is another cathode location that can result in enhanced performance due to improved coupling between the cathode and thruster discharge.

The tests reported in this paper were performed at the lowest attainable background pressure conditions and represent test conditions that are more representative of the space environment. The findings from this brief and preliminary investigation will be used to help optimize the cathode flow fraction and the location of the cathode to attain the highest possible thruster performance while maintaining stable and long life operation capability.

This paper is organized as follows: Section II provides an overview of the HiVHAc thruster test hardware and the experimental setup. Section III presents an overview of the test matrix that was completed in this test campaign. Section IV presents the experimental results for the cathode flow fraction sensitivity tests. Section V presents the experimental results for the auxiliary flow test. Section VI presents the experimental results for the cathode position study. Section VII presents a discussion of the experimental results and section VIII summarizes the test results and discusses future test plans for the HiVHAc thruster.

II. Experimental Apparatus

The major HiVHAc sub-system components that were employed during the cathode investigation were:

- The HiVHAc engineering development unit (EDU) thruster which has undergone extensive performance and thermal characterization tests in addition to a random vibration test.⁶ The EDU thruster is designed to operate at a peak discharge power of 3.9 kW and at discharge voltages up to 650 V. The thruster incorporates an in-situ discharge channel replacement mechanism for life extension. The thruster development plan has been reported earlier;⁶
- The Colorado Power Electronics (CPE) brassboard (BB) power processing unit (PPU), designated BB1 PPU;^{8,9}
- A 15 kW 600 V capable power supply;
- A laboratory hollow cathode assembly that was placed on a linear stage to vary the cathode position. This cathode unit has been used extensively with the HiVHAc thruster during the testing of the EDU thruster; and
- A laboratory xenon feed system.

Figure 1 shows a picture of the HiVHAc thruster hardware setup.

A. Vacuum Facility 5

Testing of the HiVHAc EDU thruster was performed in VF5 at NASA GRC. The main chamber of VF5 is 4.6 m in diameter and 18.3 m long. VF5 can be evacuated with cryopanel and oil diffusion pumps. For this test campaign the HiVHAc thruster was placed in VF5's main volume at the facility midsection facing away from the facility cryopanel. That was done to assure that the lowest possible background pressure conditions were attained during thruster operation. Figure 2 shows a picture of the HiVHAc thruster mounted inside VF5. Facility pressure was monitored with four ion gauges, three of which were mounted next to the thrust stand and were approximately aligned with the thruster exit plane, and the fourth being on the facility chamber wall. Manufacturer specifications state that the ion gauges are accurate to $\pm 6\%$ of reading. The locations of the gauges are shown in Fig. 2. Ion gauges 1-3 are approximately 1 m from the thruster. Ion gauges 1 and 2 are both facing downstream while ion gauge 3 is facing upstream. Ion gauges 1 and 2 agree to within 10% of each other. Ion gauge 3 reports 0.63 to 0.72 times the reading of ion gauge 2. Ion gauge 2 readings were used to determine the number of multiples of the lowest achievable background pressure that the thruster was experiencing. All reported ion gauge readings are corrected for xenon.

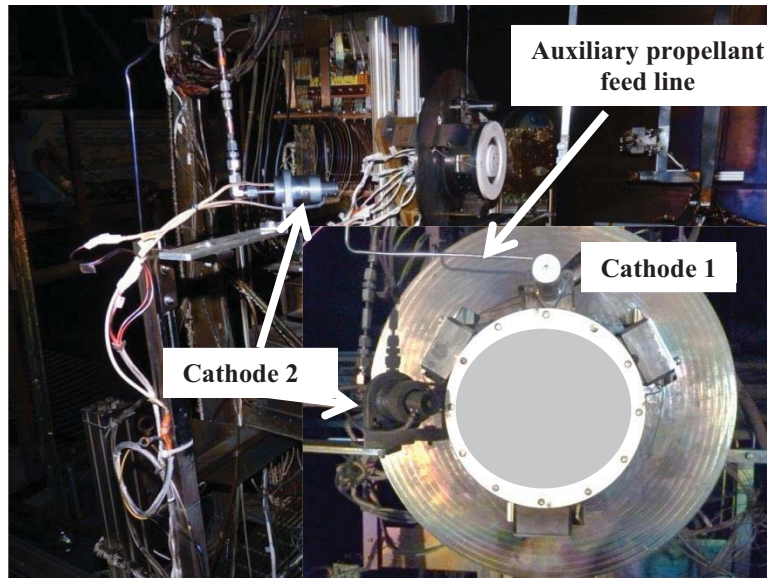


Figure 1. The HiVHAc EDU thruster mounted on the inverted pendulum thruster stand inside VF5. Denoted on the photograph are the cathode 1 assembly, cathode 2 assembly, and the auxiliary propellant feed line.

B. Laboratory Propellant Feed System

A laboratory propellant feed system was used in the HiVHAc cathode study test. The feed system supplied xenon to the thruster, the two cathode assemblies, and the auxiliary flow by cathode 1. The propellant feed system utilized four mass flow controllers (MFCs). A 200, 100, 10, and 50 sccm MFCs were used to supply xenon to the thruster, cathode 1, cathode 2, and the auxiliary cathode flow, respectively. The MFCs calibration curves indicated that the anode and cathode flow rates uncertainty is $\leq 1\%$ of set value.

C. Power Console

For this test campaign the thruster was powered with the CPE BB PPU, shown in Fig. 2. The CPE BB PPU was placed outside the vacuum chamber to allow for use of a laboratory power supply during thruster operation. The BB

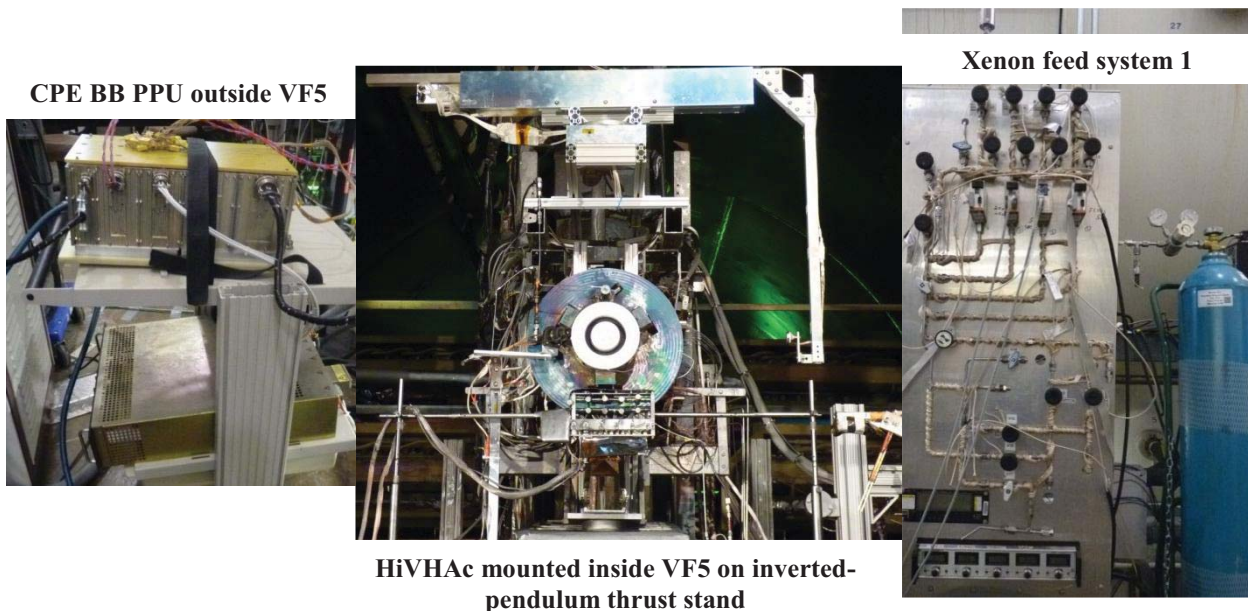


Figure 2. HiVHAc thruster test hardware.

PPU has demonstrated over 2,000 hours of operation in vacuum as was reported earlier.⁸ The PPU is powered with a 0-160 Vdc 90 A power supply. The operation of the CPE BB PPU is controlled with a control console built by CPE.

D. Inverted Pendulum Thrust Stand

A null-type water-cooled inverted pendulum thrust stand was implemented during thruster performance evaluation. The power cables were fed from the vacuum feed thrus to the thruster using a “water fall” configuration to minimize the thermal drift of the thrust stand readings. In-situ thrust stand calibrations were performed prior to, during, and after thruster testing. In addition, during thruster testing the thruster was periodically turned off to measure the thrust stand thermal drift magnitude, and the corrections were incorporated in the reported thrust. Thrust measurement uncertainty was estimated at 2% of measured value.

E. Data Acquisition

A data logger was used to measure and record the thruster operating parameters. The measurements were calibrated using a calibrated meter and they included the various thruster operating currents, operating voltages, thruster component temperatures, and facility pressure in the vicinity of the thruster.

F. Diagnostics

An extensive set of diagnostics was used to take full advantage of the opportunity to test HiVHAc EDU in VF5. These diagnostics included:

- Plasma diagnostics including a near-field Faraday probe that was mounted on an axial stage and rotary stage, and far-field retarding potential analyzer (RPA), $E \times B$ probe, and Langmuir probes. Results from the Faraday probe, RPA, $E \times B$ probe, and Langmuir probes were reported by Huang et al.¹⁰ In addition to the above diagnostics, an Air Force Research Laboratory (AFRL) high speed Langmuir probe (HSLP) rake was implemented in this test.¹¹ Analysis of the HSLP data for the pressure sensitivity test are reported in a companion paper by Huang et al.;¹²
- Fast camera imaging of the HiVHAc thruster discharge was performed using a FAST camera. Analysis of the high speed imaging camera system images during the pressure sensitivity test are reported in a companion paper by Huang et al.;¹²
- Type-K thermocouples were used to monitor the temperature of various thruster components during this test campaign. Analysis of the results is on-going and will be presented in a later publication; and
- Infrared camera imaging of the HiVHAc thruster using an Infrared camera that was placed inside a pressurized enclosure inside VF5 4 m away from the thruster. Results from the thermocouple and IR camera measurements will also be presented in a later publication.

Only a subset of these diagnostics were implemented in this study. Figure 3 shows a picture of the various diagnostics used during this test campaign.

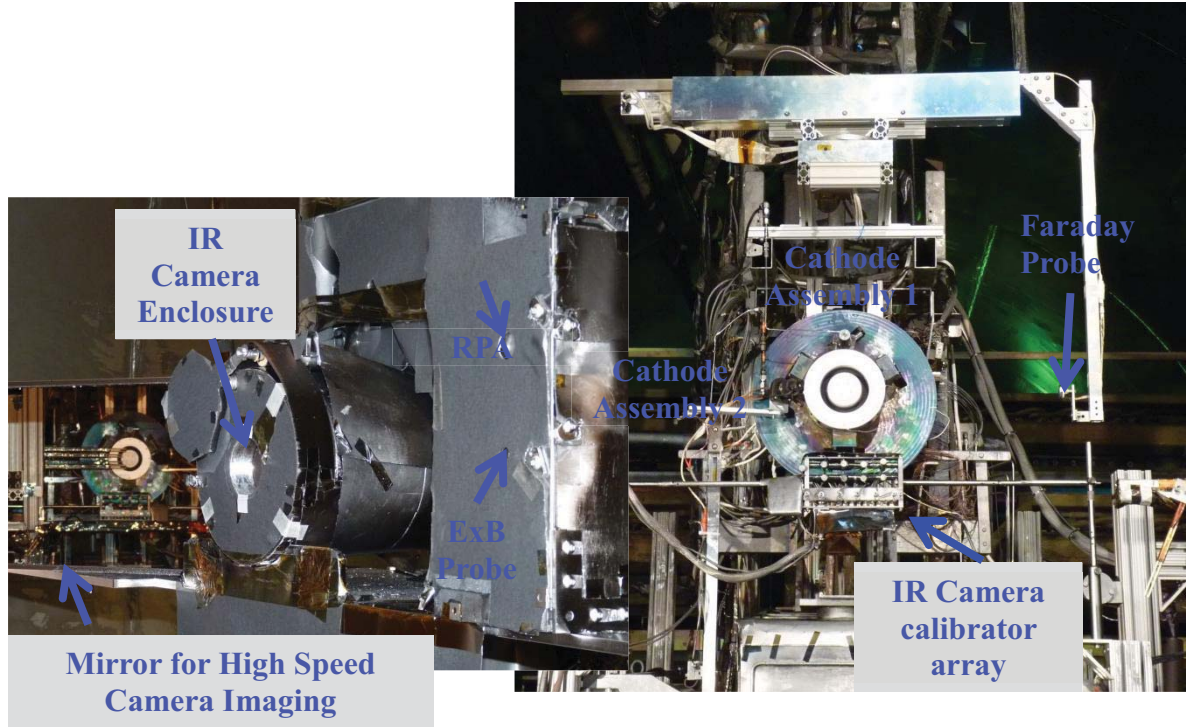


Figure 3. Photograph showing the various diagnostics implemented during the HiVHAc thruster test campaign at NASA Glenn's VF5. Also pictured is the second hollow cathode assembly used in this study.

III. Experimental Test Matrix

Table 1 presents a summary of the tests that were performed in this test campaign. As shown in Table 1, tests were performed at power levels ranging from 1 kW to 3.9 kW and at discharge voltages ranging from 300 V to 600 V. The cathode flow fraction test was performed at all the throttling conditions listed in Table 1. The cathode auxiliary injection test was not performed at 3.2 kW 400 V and 3.8 kW 500 V test conditions. Finally, the cathode position study was only performed at 3.8 kW 500 V throttle point. The test matrix listed in Table 1 includes a wide range of test conditions that will elucidate how thruster operation changes due to variations in the cathode flow fraction and the injection of auxiliary propellant at different power levels, different discharge voltages, and at different power levels for a given discharge voltage.

The data collected during this test series include thruster telemetry, discharge oscillation waveforms, thrust, and facility background pressure. Measurements from the HSLP and fast imaging camera were collected during the cathode position test segment and will be reported in a later publication.

Table 1. Summary of the HiVHAc thruster cathode study test conditions

Thruster Operation	Cathode-to-Anode Flow Fraction Test	Cathode Auxiliary Flow Test	Cathode #2 Position Sensitivity Test
1.0 kW at 300 V	√	√	
2.0 kW at 300 V	√	√	
3.0 kW at 300 V	√		
2.0 kW at 400 V	√	√	
3.2 kW at 400 V	√		
3 kW at 500 V	√	√	
3.8 kW at 500 V	√		√
3.9 kW at 600 V	√	√	

IV. Cathode-to-Anode Flow Fraction Variation Tests

The cathode flow fraction sensitivity test was performed at power levels from 1 kW to 3.9 kW and at discharge voltages from 300 V to 600 V. In general, the cathode flow fraction test evaluated thruster operation at cathode flow fractions of 5%, 7%, and 10%. Measured parameters that will be discussed in this section include the cathode-to-ground voltage, discharge current, thrust, and discharge current oscillations.

Figure 4 presents the cathode-to-ground voltage variation as a function of the cathode flow fraction. Results in Fig. 4 indicate that, in general, the cathode-to-ground voltage became more positive as the cathode flow fraction was increased. This is expected since it has been observed previously (with the HiVHAc thruster and other Hall thrusters) that increasing the cathode flow does indeed improve how the cathode plume couples to the anode discharge.¹³

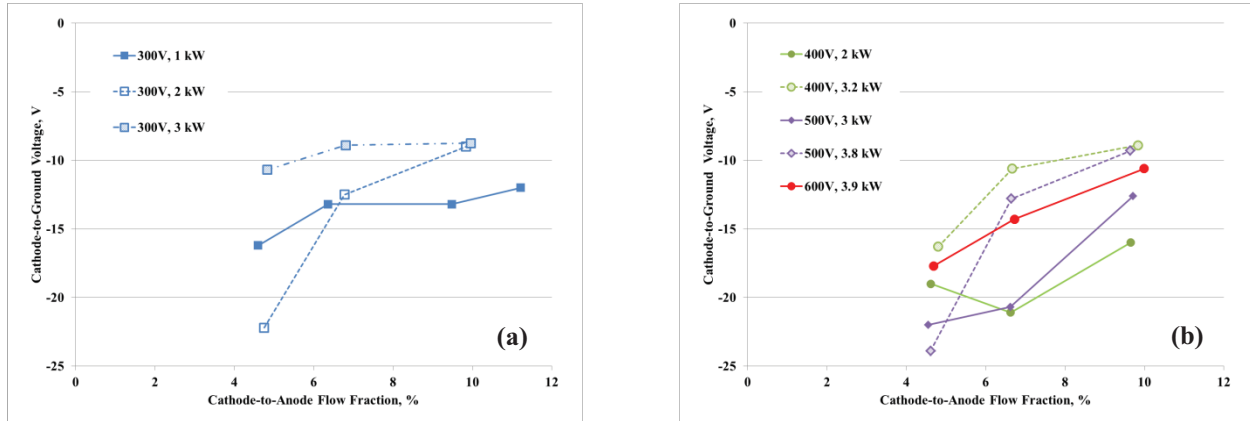


Figure 4. Cathode-to-ground voltage variations as a function of the cathode flow fraction for (a) 300V and (b) 400, 500, and 600 V thruster operation.

Figure 5 presents the percentage change in the discharge current as a function of the cathode flow fraction. The values presented in Fig. 5 show that the variation was within $\pm 1.5\%$ of the discharge current magnitude at a cathode flow fraction of 7% (nominal). At a cathode flow fraction of 5% the discharge current was lower and higher than at 7% (mixed trend), while at a cathode fraction of 10% the discharge current was mostly higher than at 7%. Inspection of the ion gauge readings next to the thruster indicates that the pressure in the vicinity of the thruster slightly increased as the cathode flow fraction was increased from 5 to 10%, as such the increase in the discharge current may be attributed to flow ingestion. This will be further discussed in Section VII.

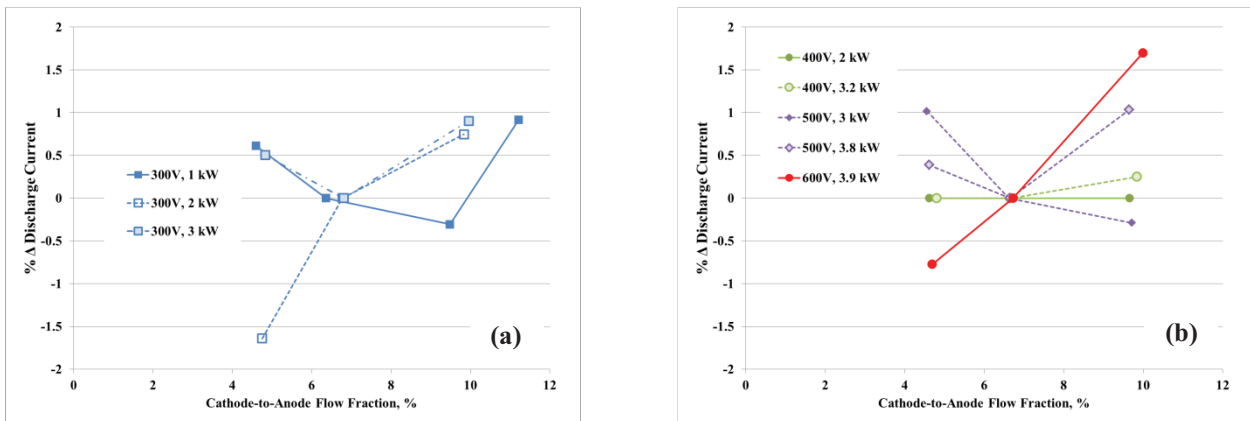


Figure 5. Percentage change in discharge current as a function of the cathode flow fraction for (a) 300V and (b) 400, 500, and 600 V thruster operation.

Figure 6 presents the percentage change in thrust as a function of the cathode flow fraction. The values presented in Figure 6 show that the variation was within $\pm 3\%$ of the thrust magnitude at a cathode fraction of 7% (nominal flow fraction). Due to the fact that the thrust measurement uncertainty is within 2% it is difficult to draw

conclusions from the observed trends, but in general one can conclude that variation in thrust was minimal as the cathode flow fraction was increased and that thrust tended to increase with increased cathode flow fraction.

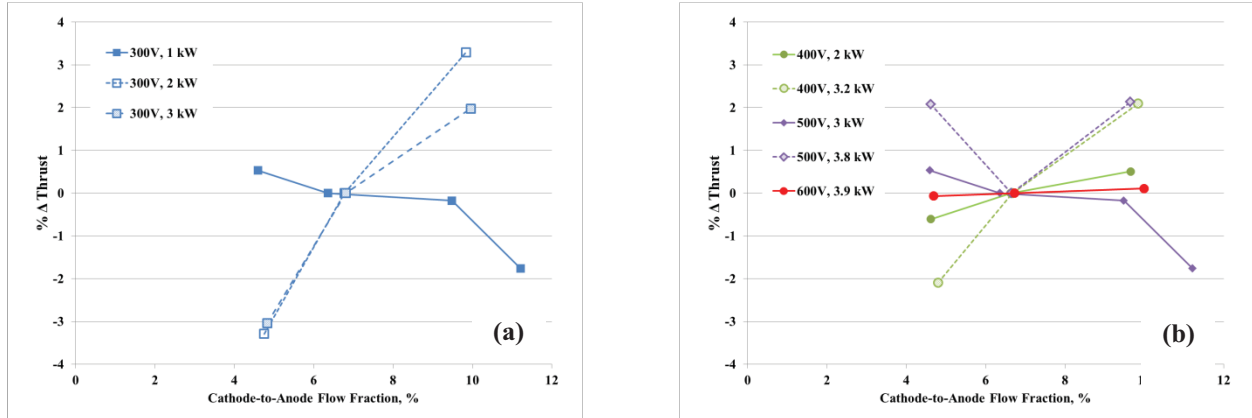


Figure 6. Percentage change in thrust as a function of the cathode flow fraction for (a) 300V and (b) 400, 500, and 600 V thruster operation.

In general, it was observed that the discharge current oscillation peak-to-peak magnitude increased slightly as the cathode flow fraction was decreased from 7 to 5%. When the cathode flow fraction was increased from 7 to 10% the discharge current oscillations peak-to-peak magnitude also increased slightly. Table 2 presents a summary of the discharge current peak-to-peak oscillations for 3 kW 300 V, 3.2 kW 400 V, and 3.8 kW 500 V thruster operation. Results in Table 2, generally indicate that the lowest discharge current oscillations magnitude were attained for 7% cathode flow fraction. The results in Table 2 show that the oscillations levels tended to increase at flow rates higher and lower than the nominal 7%. Figure 7 presents the discharge current waveforms (in yellow) for the 3.2 kW 400 V thruster operation. At a cathode flow fraction of 5%, 7%, 10%, and 15%, the peak-to-peak discharge current was ± 2.1 A, ± 1.8 A, ± 2.1 A, and ± 2.5 A, respectively. As such no significant variation in the discharge current oscillations magnitude was observed due to changes in the cathode flow fraction.

Table 2. Discharge current peak-to-peak oscillations for 3.0 kW 300 V A V, 3.2 kW 400 V, and 3.8 kW 500 V A at various cathode flow fractions (CFF).

CFF, %	Discharge Current Peak-to-Peak Oscillations Magnitude		
	3.0 kW 300 V	3.2 kW 400 V	3.8 kW 500 V
5	1.84	4.2	6.8
7	1.72	3.8	6.6
10	4	4.2	5
15		5	

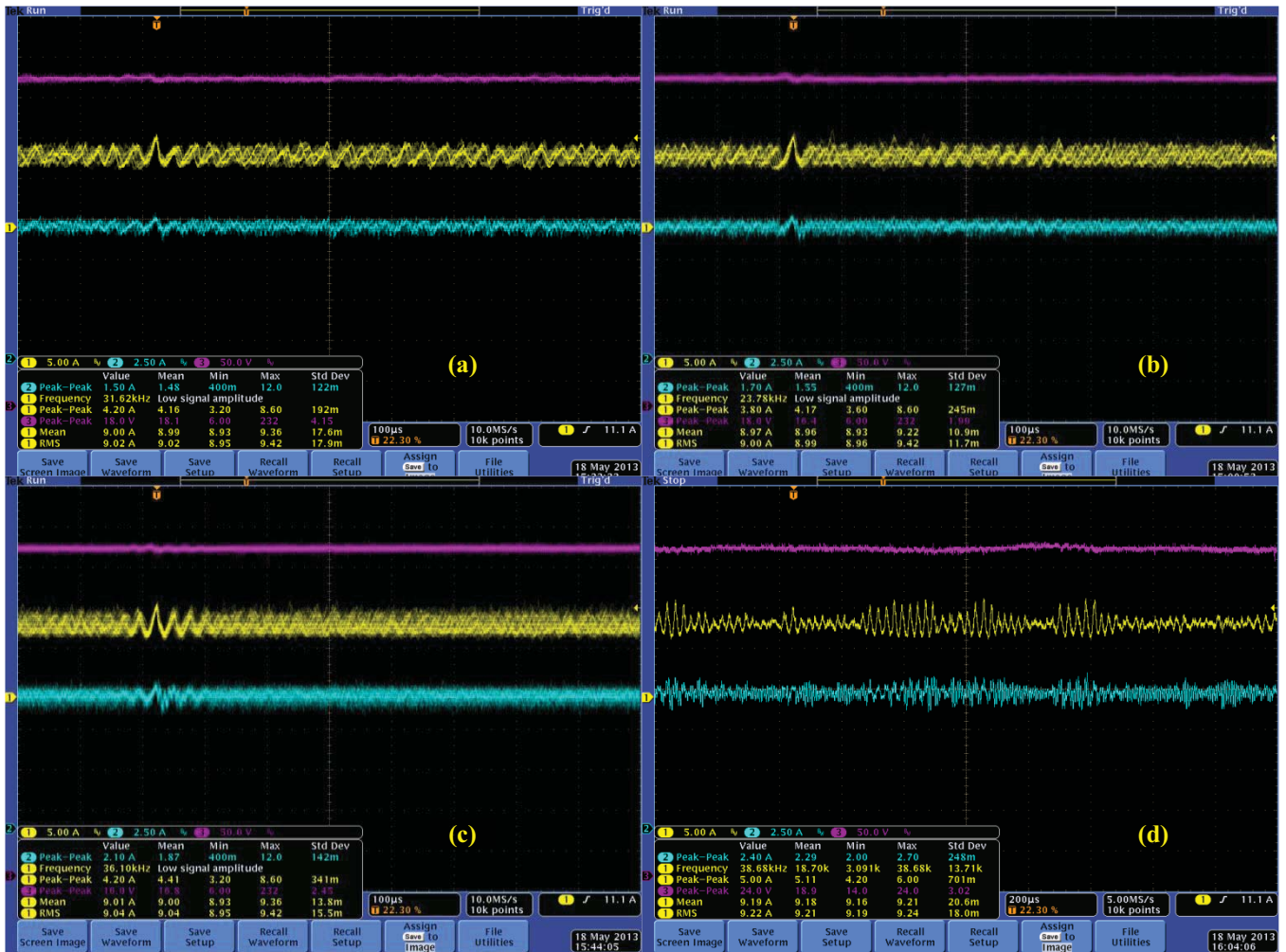


Figure 7. Discharge current waveforms for thruster operation at 3.2 kW, 400 V for cathode flow fraction of 5% (a), 7% (b), 10% (c), and 15% (d).

V. Auxiliary Flow Variation Test

For this test segment auxiliary xenon flow was injected in the vicinity of cathode 1 assembly to investigate the impact of this additional flow on the operational characteristics of the HiVHAc thruster. The other benefit that can be attained from this additional injected flow is a reduction in the keeper erosion rate as was shown by Chu *et al.*¹⁴ Figure 1 shows the location of the auxiliary propellant feed line with respect to the HiVHAc thruster and cathode 1 assembly. Tests were performed for thruster operating throttle points that were outlined in Table 1. In this test segment, the auxiliary flow rates tested were 0.18, 0.28, 0.39, 0.49, and 0.69 mg/s. Figure 8 shows a photograph of the HiVHAc thruster operating at 1 kW, 300 V with an auxiliary flow of 0.69 mg/s. As can be seen in Fig. 8, the cathode plume became more luminous and the plasma bridge between the cathode and thruster became more visible and pronounced.

Figure 9 presents the variation of the cathode-to-ground voltage as a function of the auxiliary flow. The results in Fig. 9 indicate that the cathode-to-ground voltage becomes more positive with increasing auxiliary flow rate. This is an indication of improved coupling between the cathode plume and the discharge. This trend

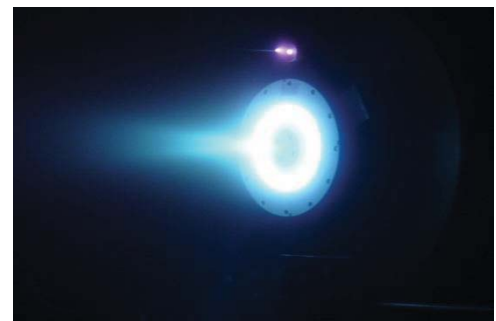


Figure 8. Photograph of the HiVHAc thruster operating at 1 kW and 300 V with an auxiliary flow of 0.69 mg/s.

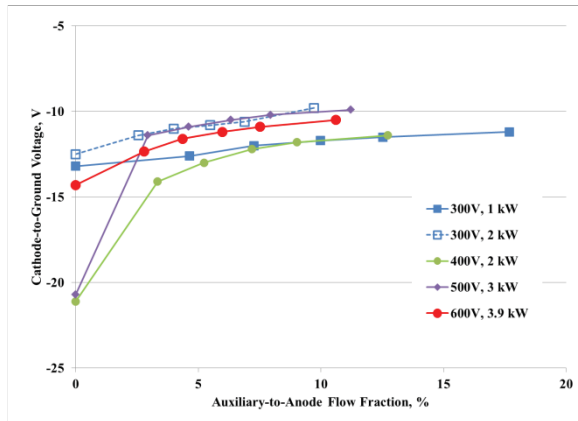


Figure 9. Cathode-to-ground voltage variation as a function of the auxiliary flow rate.

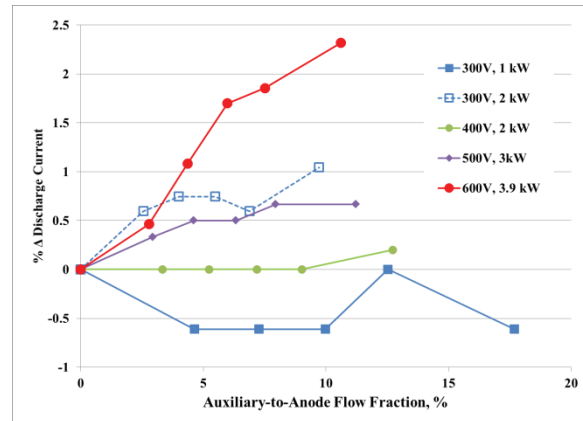


Figure 10. Percentage change in discharge current as a function of the auxiliary flow rate.

was observed for all thruster operating conditions listed in Table 1.

Figure 10 presents the percentage change in the thruster's discharge current as a function of the auxiliary flow. For the most part (other than at 1 kW and 300 V), the discharge current of the thruster increased slightly with the injection of the secondary xenon propellant. For all the test conditions listed in Table 1, the increase was approximately less than 1% except for the 3.9 kW, 600 V test condition where the percentage increase in the discharge current was around 2.5% for an auxiliary flow of 0.69 mg/s. The increase in the discharge current is most likely due to the discharge moving upstream and resulting in glowing of the tip of the erosion zone causing an elevation in the discharge current.⁷

Figure 11 presents the percentage increase in thrust as a function of the auxiliary flow. In general, it is observed that thrust increases slightly with increased auxiliary flow rate. This trend was observed for all thruster operating conditions. It is postulated that a portion of the injected flow is ingested by the thruster and is resulting in increased thrust. Further discussion of the results is presented in Section VII.

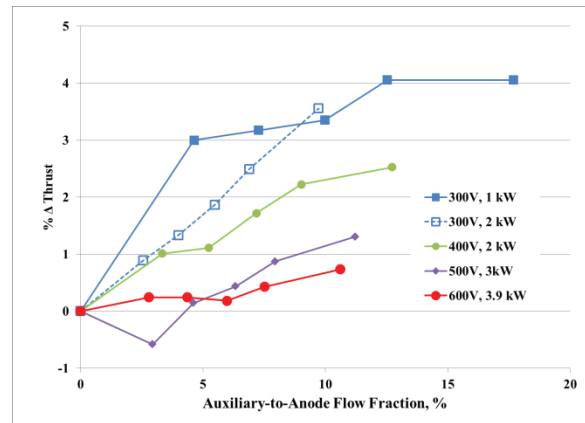


Figure 11. Percentage change in thrust as a function of the auxiliary flow rate.

VI. Cathode Position Variation Test

The cathode 2 position was varied to evaluate the impact of the cathode position on thruster operation. The position of the cathode was varied from 1 mm to 600 mm away from the distance of closet approach to the thruster. Figure 1 shows a photograph of the cathode 2 at the location of closet approach. This test was only performed for the thruster operating at 3.8 kW and 500 V. Figure 12 shows photographs of the thruster operation with the cathode positioned at different radial locations away from the thruster. Figure 12 (a) shows the thruster operating with cathode 2 located at 1 mm from the closet approach position. In this location, the plasma bridge between the cathode and thruster discharge is very visible and can be seen from outside of VF5. As the cathode is moved radially away from the thruster the plasma bridge intensity is maintained, but then starts to "fade" at a distance of approximately 100 mm away from the closet approach position. At a distance of 200 mm and above, visual detection of the plasma bridge is very difficult and all that can be seen from outside of VF5 is the cathode spot. Figure 13 presents the variation in the cathode-to-ground voltage and percentage change in thrust as a function of the cathode position. As can be seen from Fig. 13, the cathode-to-ground voltage becomes more positive as the cathode is moved away from the thruster. However, thrust magnitude is initially increasing as the cathode is moved away from the thruster but at a distance of approximately 100 mm, the thrust starts to drop and continues to drop as the cathode is moved further away from the thruster.

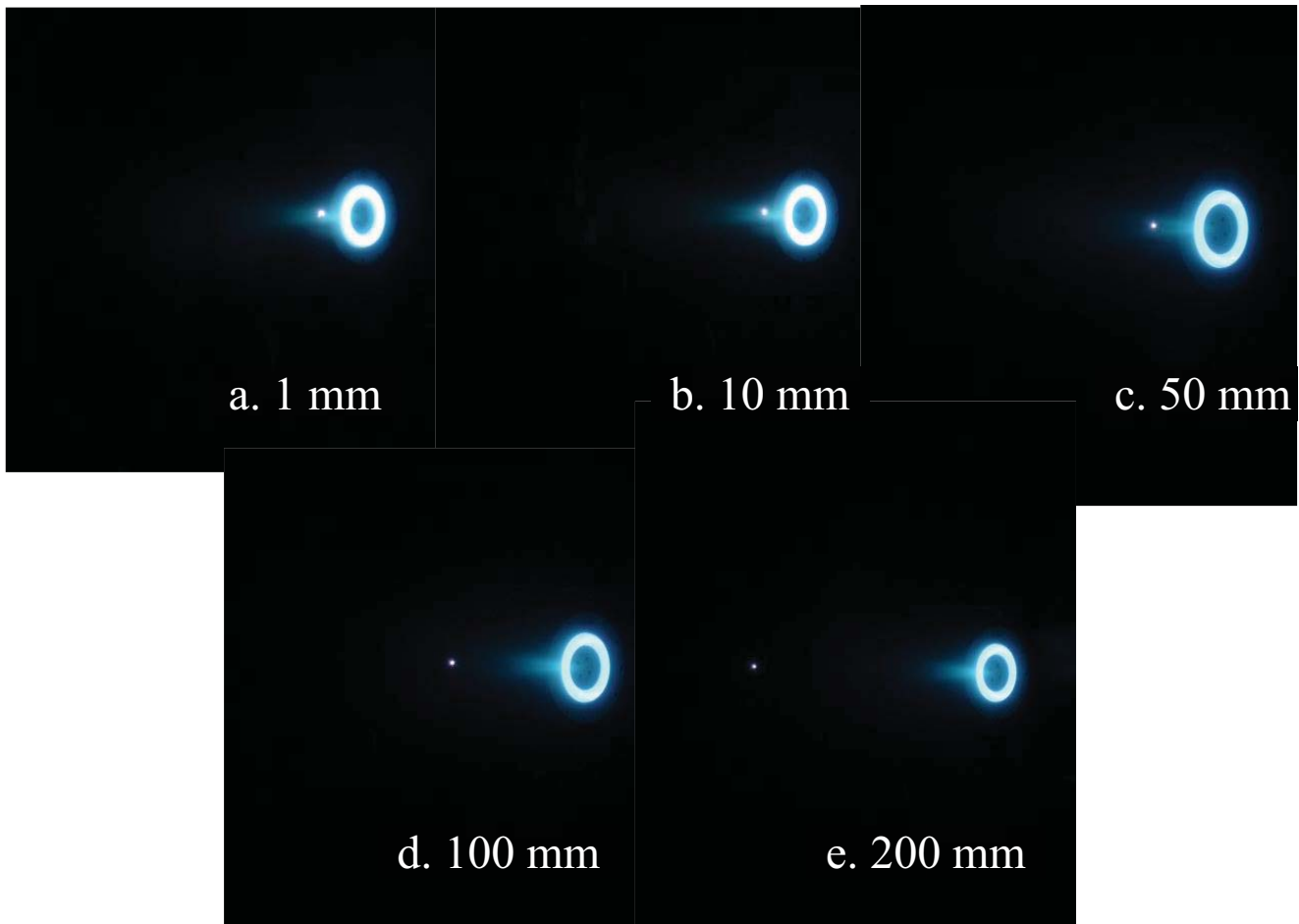


Figure 12. Photographs showing the HiVHAc thruster operation with cathode 2 located at (a) 1 mm, (b) 10 mm, (c) 50 mm, (d) 100 mm, and (e) 200 mm from distance of closet approach.

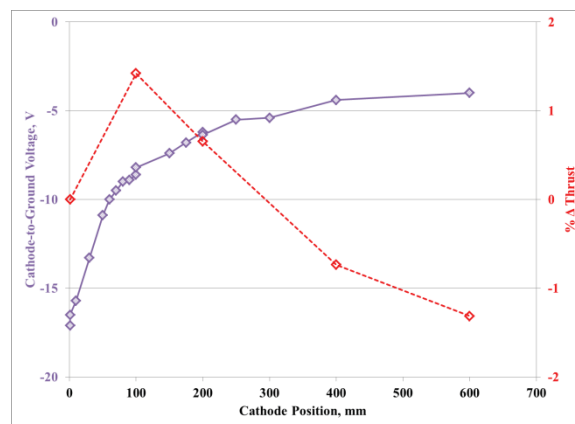


Figure 13. Variation in cathode-to-ground voltage and percentage change in thrust as a function of cathode position for thruster operation at 3.8 kW and 500 V.

VII. Discussion

The tests performed in this investigation provided insights into the effect of varying the cathode flow fraction, injection of auxiliary flow, and cathode position on the thruster operational characteristics and performance in the lowest background pressure conditions for the HiVHAc thruster. During this test campaign when the thruster was operating at 3 kW, 300 V the corresponding anode flow rate was 10.2 mg/s (highest flow rate achieved during this investigation) and the ion gauge 2 reading was 2.6×10^{-6} Torr-Xe. The cathode 1 position was selected based on criteria developed by Tilley *et al.*¹⁵, which positions the cathode in a location with improved cathode coupling to the discharge and low cathode erosion.

In general, it was observed that reducing the cathode flow fraction from the nominal value of 7% resulted in the cathode-to-ground voltage becoming more negative, and increasing the cathode flow fraction from 7 to 10% resulted in the cathode-to-ground voltage becoming more positive as shown in Fig. 4. These trends have been observed in other Hall thrusters.¹³ These trends persisted for all thruster operating power and discharge voltage levels presented in this paper. A lower cathode-to-ground voltage (more negative) may indicate an increase in the plasma potential relative to the cathode (higher magnitude coupling voltage), this higher plasma potential would theoretically result in lower thrust due to a reduction in the thruster's voltage utilization efficiency. As for the discharge current, a mixed trend that was observed in Fig. 5. Results in Fig. 5 indicate that discharge current both increased and decreased with increased cathode flow fraction. It is speculated that the reason for the slight increase in discharge current is partly due to flow ingestion caused by the higher neutral density from the cathode (higher ion gauge readings were observed for the high cathode flow fractions). It is not clear why the discharge current decreased for some of the test conditions, but since the reduction in the discharge current was within the uncertainty of the measurement no further conclusions are drawn; additional measurements would be needed to further elucidate what was occurring. Thrust, as is shown in Fig. 6, tended to increase with increased cathode flow fraction, although in some test conditions it decreased. An increasing thrust magnitude could be attributed to increased ion beam current (due to flow ingestion) and better coupling between the cathode and the discharge (the cathode-to-ground voltage becomes more positive). However, the increase in thrust was mostly within the uncertainty of the measurement for most of the test cases listed in Table 1. The cathode flow fraction also did not significantly alter the discharge current peak-to-peak oscillations magnitude. The test results indicated that the peak-to-peak discharge current oscillations increased by approximately 15% of their nominal values at the 7% cathode flow fraction when the cathode flow fraction was dropped to 5%. A similar increase was also observed when the cathode flow fraction was changed from 7 to 10%. The results presented in Figs. 4-7 and Table 2 present a "global" view of the impact of varying the cathode flow fraction on thruster operation and performance. Results presented in Figs. 4-7 and Table 2 indicate that reducing the cathode flow fraction to 5% (from the nominal 7% value) resulted in a slight increase in the discharge current oscillations without any significant increase in thruster performance. Increasing the cathode flow fraction to 10% (from the nominal value of 7%) also increased the discharge current oscillations magnitude. Computing the total thrust efficiency for the various test conditions indicated at some operating points the performance improved with increased cathode flow fraction while at other operating points it decreased. The range of change in the total thrust efficiency was $\pm 2.5\%$ of the value at the nominal cathode flow fraction of 7%. This small change in the thruster total efficiency is in essence indicating that thrust efficiency is almost invariant to the cathode flow fractions that were evaluated in this study. Finally, the total specific impulse increased with reduced flow fraction (by approximately 1-2%) and decreased with increased cathode flow fraction (up to -4%), which was expected simply due to the change in total flow.

Injection of auxiliary flow near cathode 1 had a similar effect as increasing the cathode flow fraction. As is shown in Fig. 8, the cathode-to-ground voltage became more positive as the cathode auxiliary flow increased. This is indicating that the coupling between the cathode and thruster discharge is improving due to changes in plasma potential profile in the plume region. The largest reduction in the absolute magnitude of the cathode-to-ground voltage typically occurred when 0.18 mg/s was injected; injection of additional flow further reduced the absolute magnitude of the cathode-to-ground voltage by relatively small values. This indicates that significant changes in plasma potential and coupling between the cathode and thruster discharge can be gained with the addition of minimal flow, and the addition of more flow will not greatly enhance that coupling. It is postulated that the injection of auxiliary flow might be a preferred method for improving the coupling between the cathode and thruster when compared to injection of the additional flow through the cathode. It has been shown that increased cathode flow results in higher pressure inside the cathode tube resulting in increased density by the cathode orifice plate, that leads to more flux to the emitter surface and higher emitter temperatures which may reduce cathode life.^{16,17} Additionally, it has been shown that external gas injection (similar to the auxiliary flow injection scheme) reduces energetic ion production by the keeper which will increase cathode life.¹⁴ The increase in discharge current and

thrust with increased auxiliary flow is partly due to the ingestion of the additional neutral propellant, changes to the location of the discharge may also be contributing to the change in thruster performance and behavior. For all the test conditions, the total thrust efficiency and specific impulse decreased with increased auxiliary flow rate. Finally, it is postulated that increased neutral flow density in the cathode vicinity results in improved electron mobility which is the main driver for the coupling voltage becoming more positive with increased cathode flow fraction and injection of auxiliary flow.

Finally, the variation of the cathode position at 3.8 kW, 500 V indicated that the cathode-to-ground voltage monotonically decreased as the cathode was moved radially away from the thruster, whereas thrust initially increased and then started to decrease at distances greater than 100 mm away from the closest approach position. The trends observed in Fig. 13 with the cathode-to-ground voltage are qualitatively similar to trends observed in other Hall thrusters.^{18,19} Varying the cathode position relative to the thruster's magnetic field will impact how the cathode couples to the thruster discharge. The results indicate that for distances up to 100 mm away from the distance of closest approach, the cathode coupling and thruster performance improve. This is indicating the electron mobility in the plume is enhanced as the cathode is moved away. Visual observation of the thruster operation also confirmed that the plasma bridge between the cathode and thruster was very visible and pronounced. As the cathode was moved further away beyond 100 mm, the intensity of the plasma bridge started to decline. At around 200 mm away, the plasma bridge could not be visually detected. As is illustrated in Fig. 13, the thruster continued to operate normally even when the cathode was 600 mm away from the thruster but the plasma bridge between the cathode and thruster was not visually detectable. It is speculated that moving the cathode away from the thruster is initially increasing thrust due to enhanced coupling to the discharge (lower cathode-to-ground and plasma coupling voltage). However, as the cathode is moved beyond the 100 mm distance, the concurrent decrease in both the cathode-to-ground voltage and thrust is indicating that the cathode may not coupling directly to the thruster but may be coupling through other possible paths. Analysis of the far-field Faraday probe, $E \times B$ probe, RPA, HSLP and fast imaging camera measurements will be performed to further elucidate the mechanisms that were occurring during the cathode position investigation. Specifically knowledge of how the plasma potential changes as the cathode was moved away will help further elucidate what was happening to as the cathode was moved radially outward. Finally, correlation of the HiVHAc magnetic field properties (field strength and direction) at 100 mm are being used to guide the repositioning of cathode 1 in order to improve cathode coupling and thruster performance.

VIII. Summary

Cathode sensitivity tests of the HiVHAc thruster were performed in NASA GRC's VF5 at background pressure conditions that were at least six times lower than what has been achieved in the past. Assessment of the thruster operation at the nominal cathode flow fraction of 7% indicated that the thruster operated stably. Investigation of HiVHAc operation at cathode flow fractions of 5 and 10% indicated very slight differences in thruster operation and the test results did not indicate any benefits from changing the nominal HiVHAc cathode flow fraction of 7%. Investigation of injection of auxiliary flow in the vicinity of the cathode did improve cathode coupling but it was at the expense of overall thruster performance. Finally, a preliminary investigation of cathode position impact on thruster performance was performed. The results indicated that there exists a location where cathode coupling and thruster performance are enhanced. Finally, the HiVHAc project will test in the near future a HiVHAc thruster with a centrally mounted cathode to further assess the effect of cathode position on thruster performance and stability.

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